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(54) **SMART JUNCTION BOX FOR A
PHOTOVOLTAIC SYSTEM**

(71) Applicant: **Enphase Energy, Inc.**, Petaluma, CA
(US)

(72) Inventor: **Martin Fornage**, Petaluma, CA (US)

(73) Assignee: **Enphase Energy, Inc.**, Petaluma, CA
(US)

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CPC **H01L 31/02008** (2013.01); **H02H 7/20**
(2013.01)

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USPC 361/82
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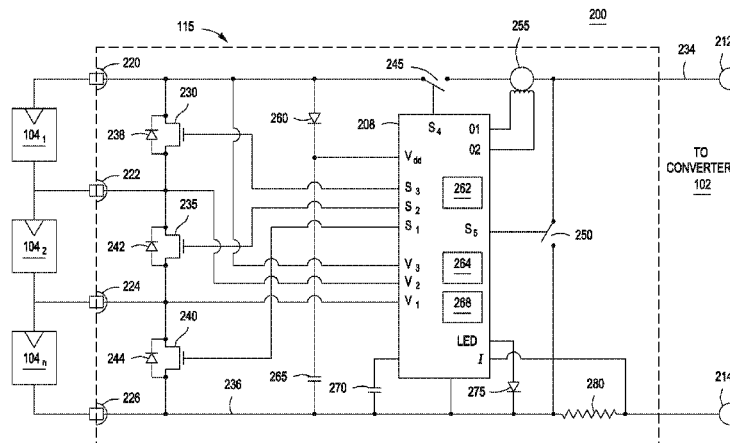
Primary Examiner — Dharti Patel

(74) *Attorney, Agent, or Firm* — Moser Taboada

(57) **ABSTRACT**

A method and apparatus for a smart junction box including: a first set of switches connected across input terminals adapted for connection to output terminals of a plurality of photovoltaic (PV) modules, a plurality of diodes connected across input terminals of each respective switch in the first set of switches, at least one reverse current detection device on at least one output terminal of the smart junction box, a second set of switches to selectively disconnect and short circuit output terminals of the smart junction box when a reverse current is detected, and wherein at least one switch of the second set of switches is located across the output terminals, a controller for controlling the first and second set of switches.

20 Claims, 7 Drawing Sheets



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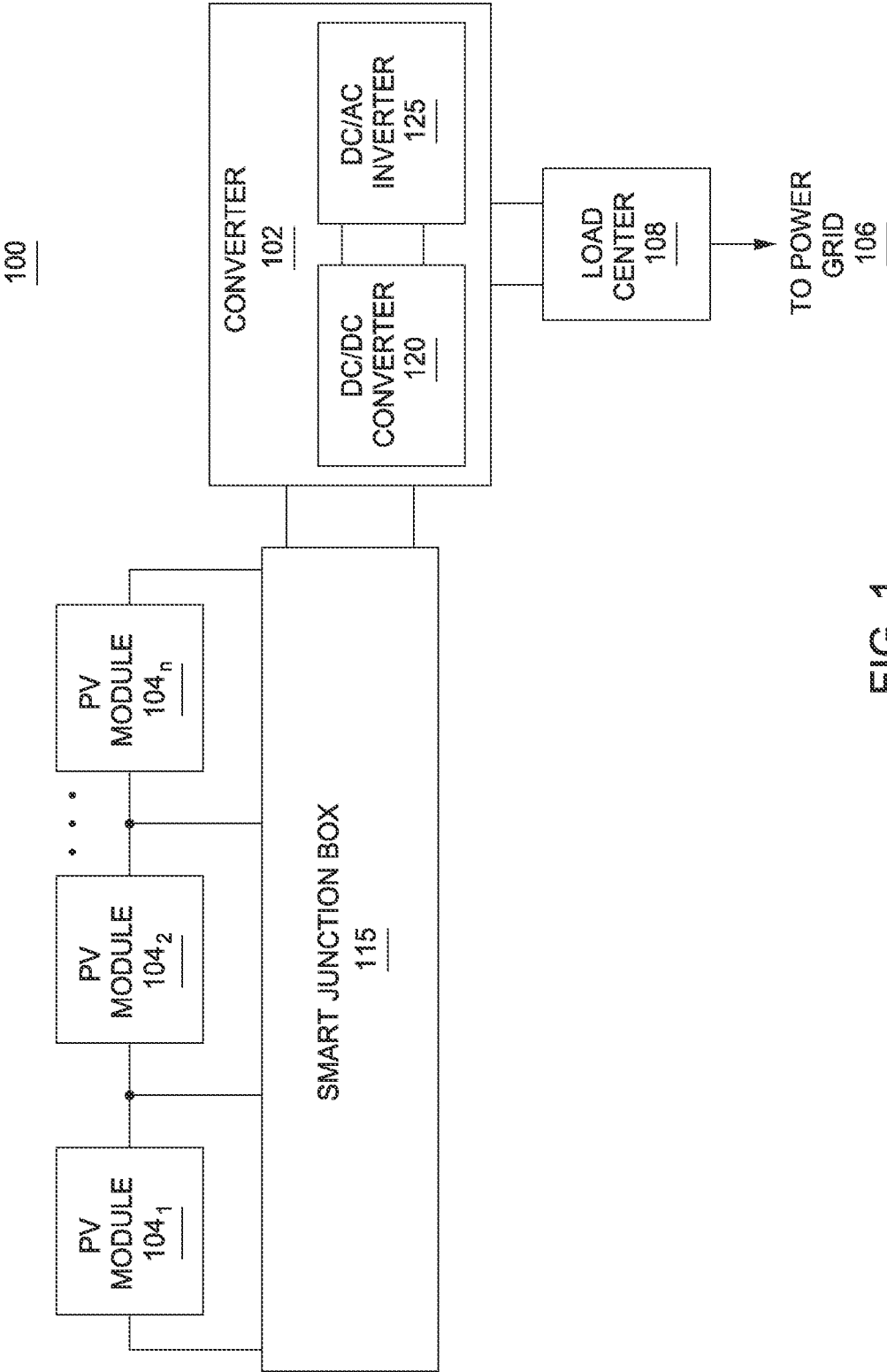
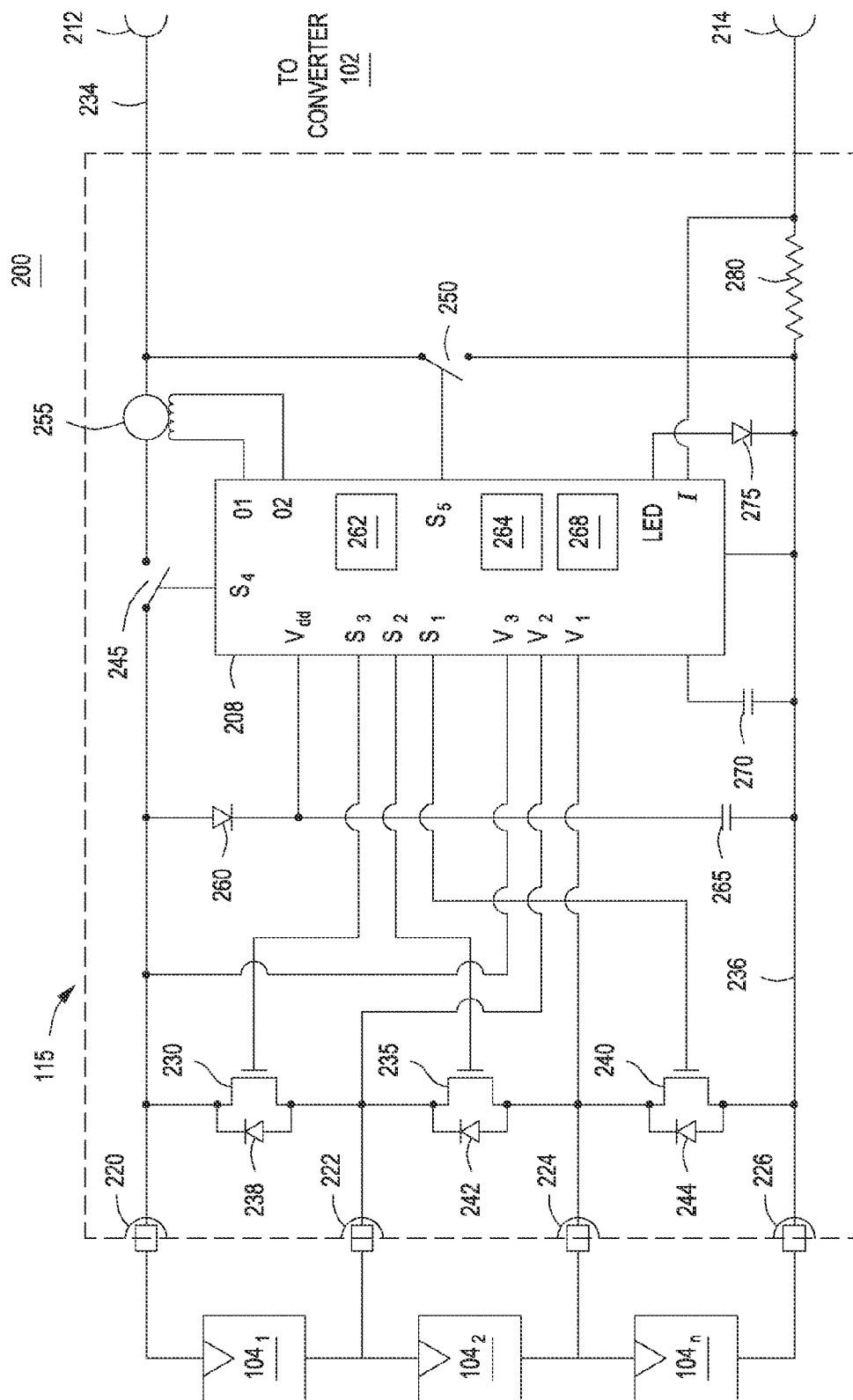


FIG. 1



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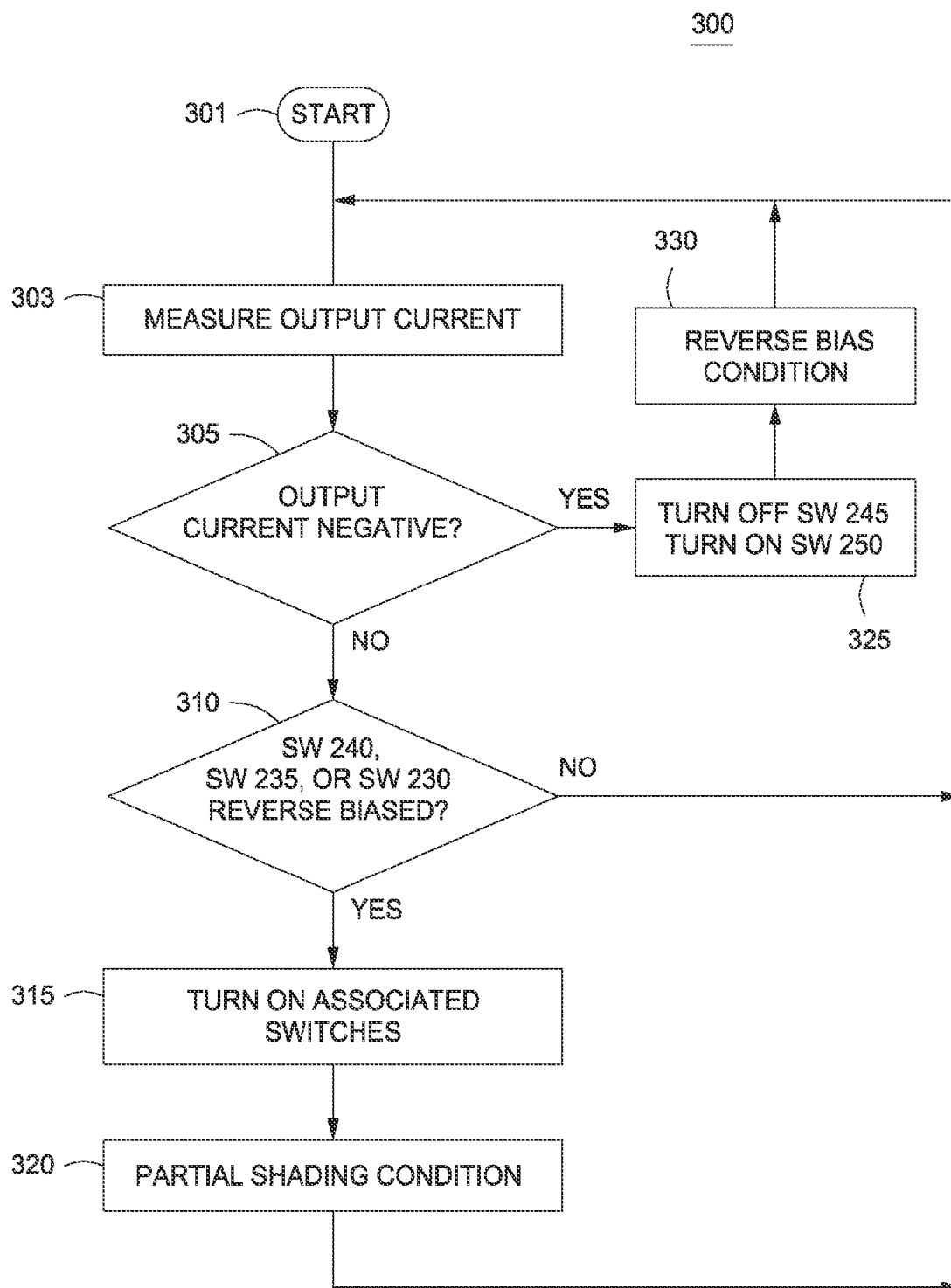


FIG. 3

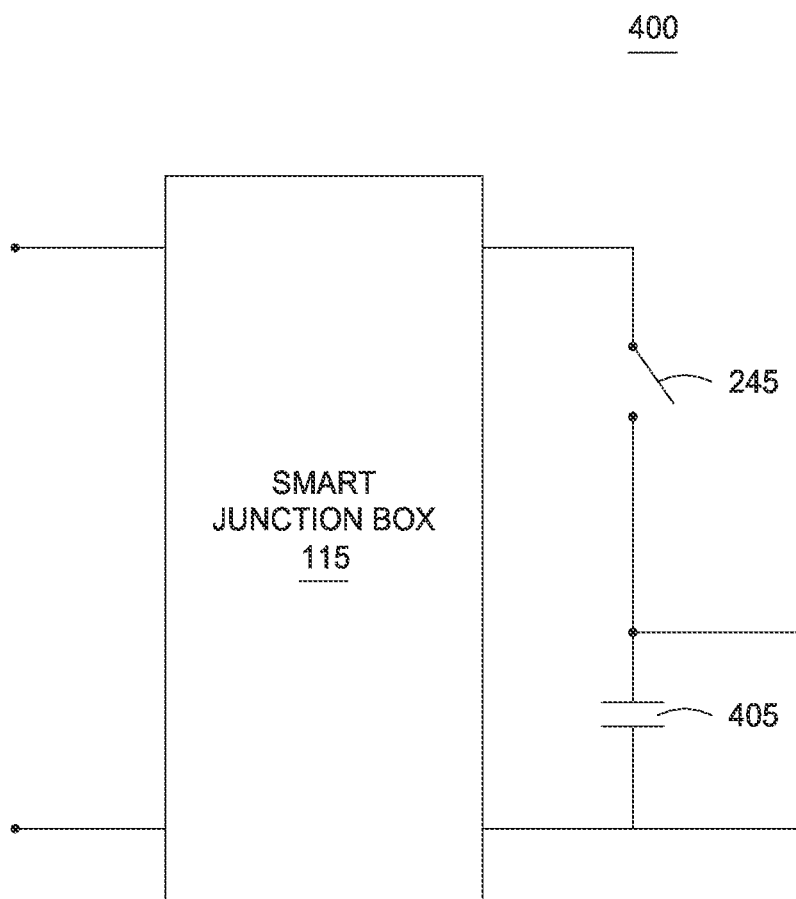


FIG. 4

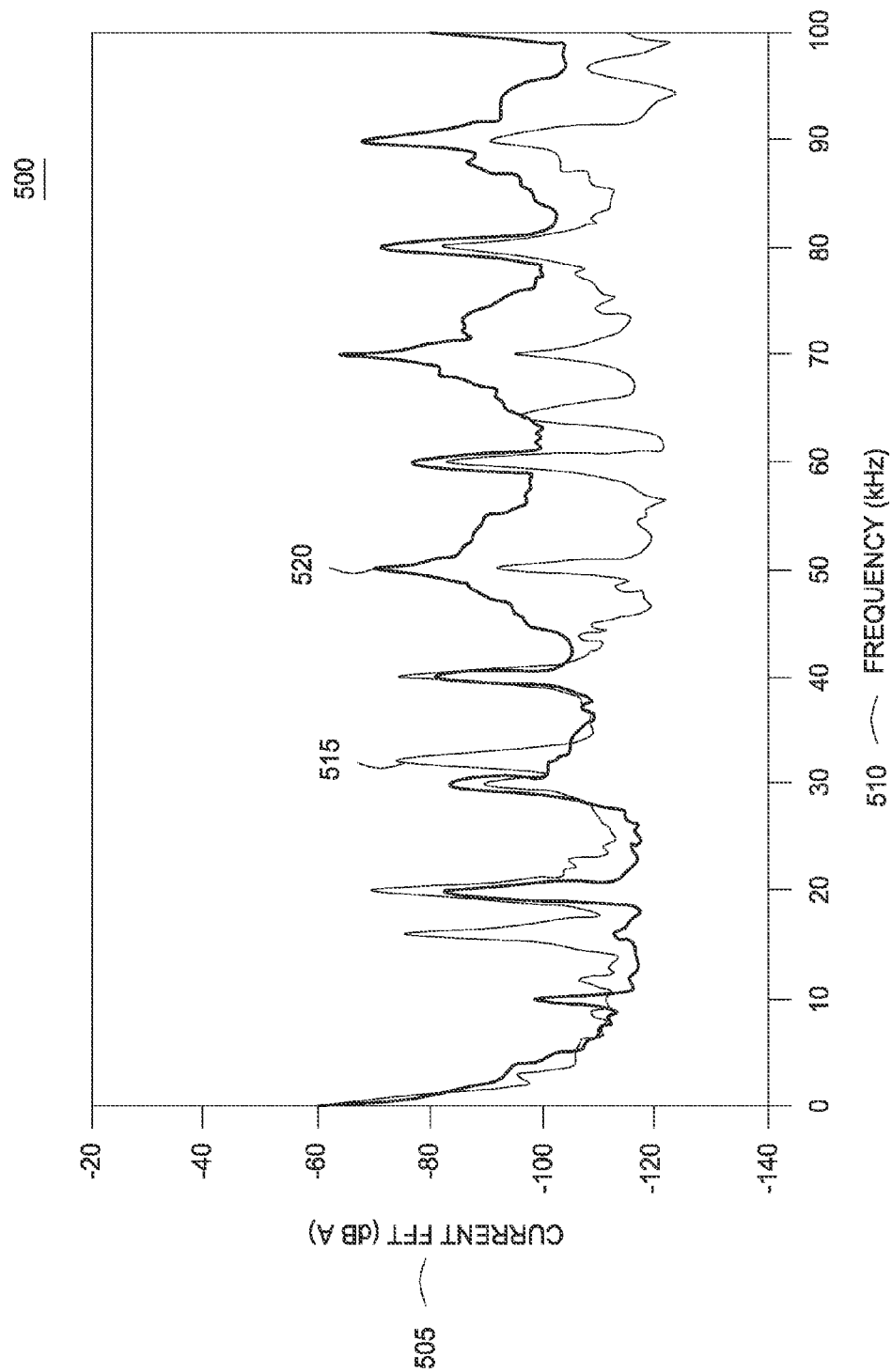
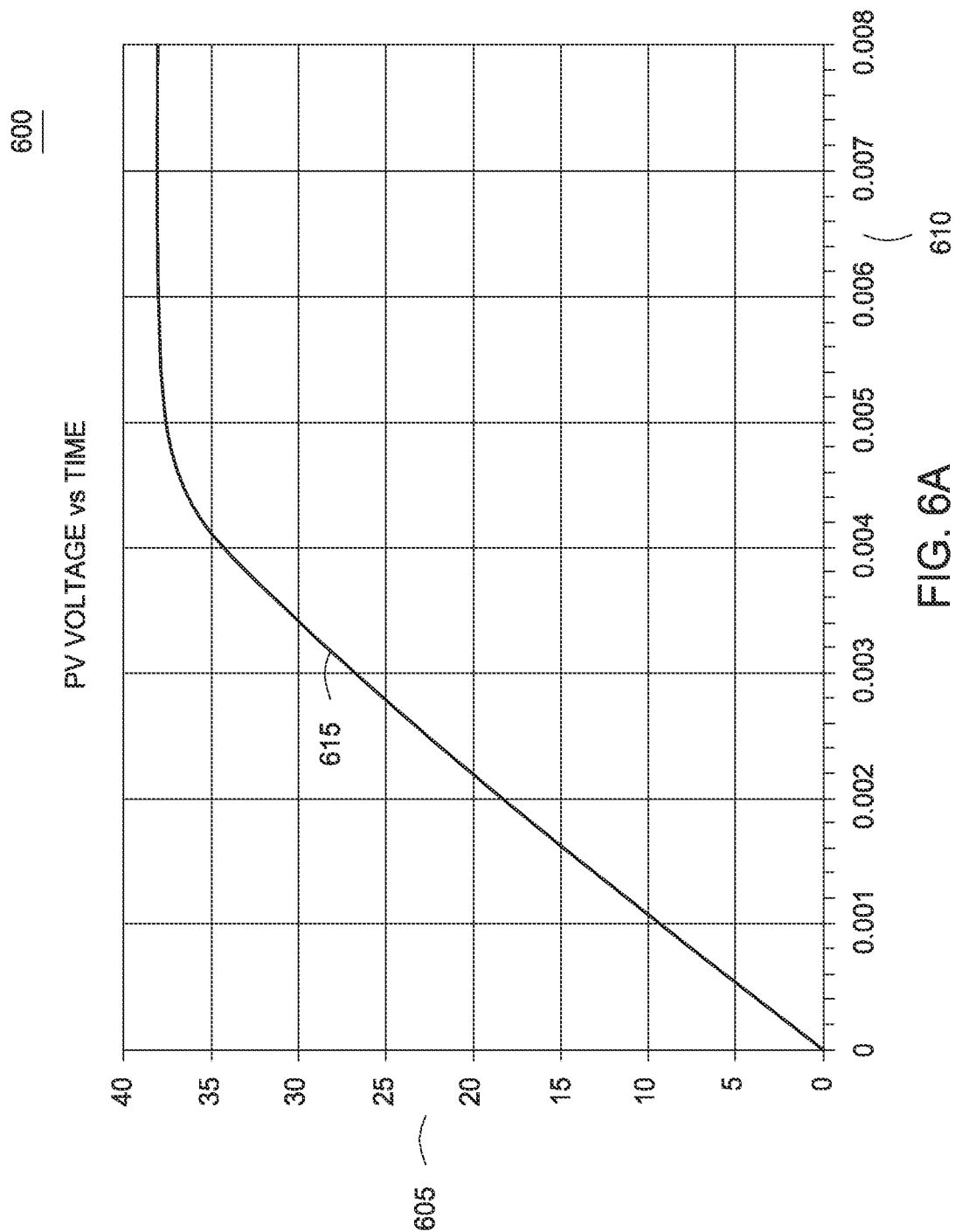
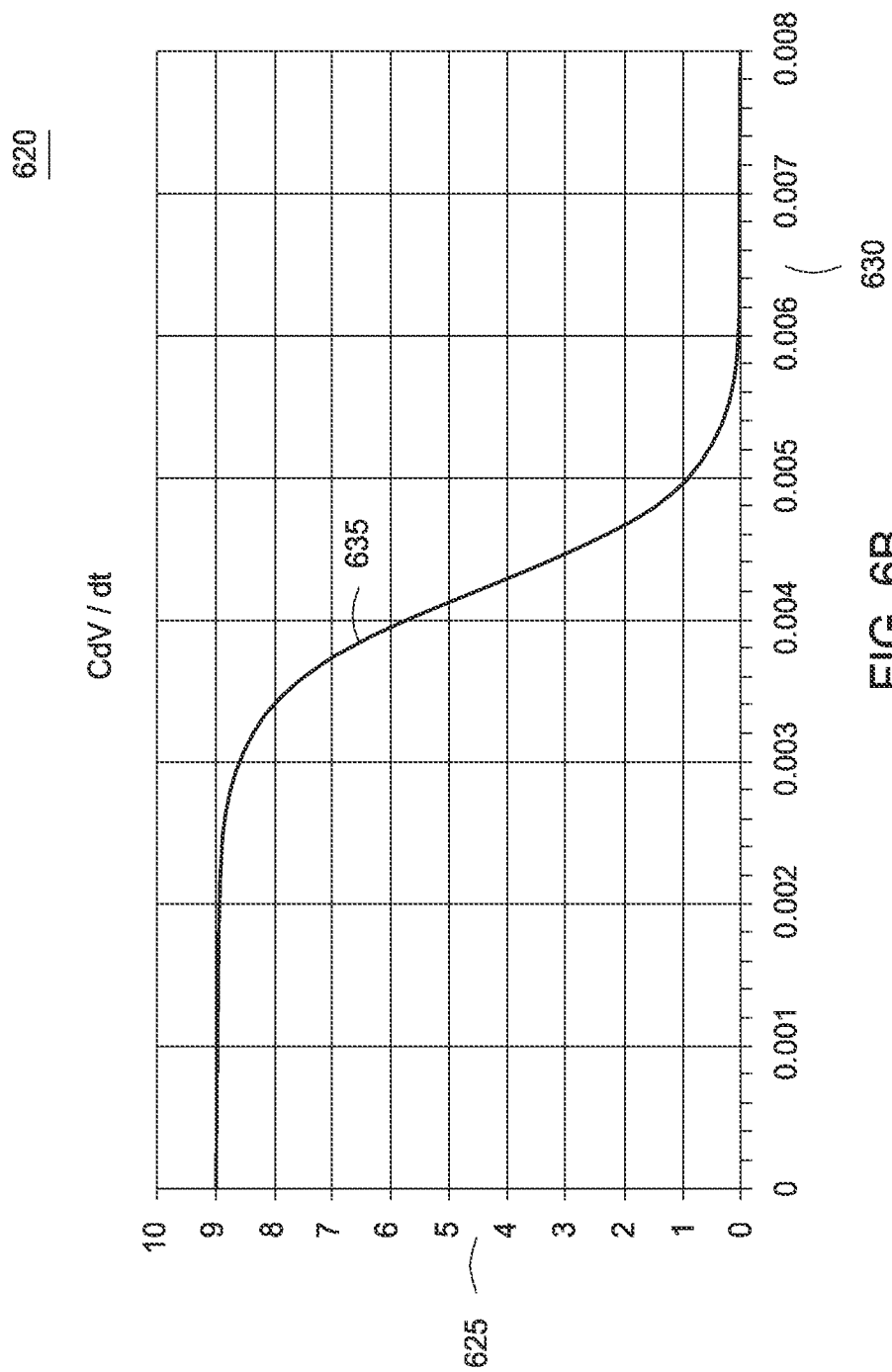


FIG. 5





SMART JUNCTION BOX FOR A PHOTOVOLTAIC SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

This Application claims priority to U.S. Provisional Patent Application No. 61/738,758 filed on Dec. 18, 2012, which is incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

Embodiments of the present disclosure generally relate to renewable energy power systems and, more particularly, to a method and apparatus providing a smart junction box in photovoltaic (PV) system.

2. Description of the Related Art

The worldwide growth of energy demand is leading to a durable increase in energy cost. In addition, it is now well established that the fossil energy reserves currently being used to generate electricity are rapidly being depleted. These growing impediments to conventional commercial power generation make solar modules a more attractive option to pursue.

Solar modules, or photovoltaic (PV) modules, convert energy from sunlight received into direct current (DC). The PV modules cannot store the electrical energy they produce, so the energy must either be dispersed to an energy storage system, such as a battery or pumped hydroelectricity storage, or dispersed by a load. One option to use the energy produced is to employ inverters to convert the DC current into an alternating current (AC) and couple the AC current to the commercial power grid. The power produced by such a distributed generation (DG) system can then be sold to the commercial power company, or used to offset local consumption of electricity by local loads.

PV modules within an array only generate equal amounts of power if exposed to a uniform amount of sunlight. However, should a single module be shaded (e.g., by a tree or cloud) or module become nonfunctioning, the power generated is inefficiently transferred and may adversely affect the shaded module. For example, the operating current of the overall series string approaches the short-circuit current of the singular shaded module and the overall current becomes limited by the shaded module. The extra current produced by the unshaded PV modules then forward biases the remaining PV modules.

If the series string is short circuited, then the forward bias across the unshaded PV modules causes a reverse bias on the shaded module. Thus a large number of series connected PV modules may cause a large reverse bias across the shaded module, leading to large dissipation of damaging power into the shaded module. Bypass diodes placed in the junction box have been used to protect the shaded PV module, however such diodes can dissipate an excess of 10 W when energized. The dissipation leads to high elevated temperatures in the junction box and possible thermal run away of the diodes.

Furthermore, continued power generation and conversion when a PV module is damaged may lead to arc faults which are extremely dangerous. The DC PV modules will continue to provide energy into a short circuit or an arcing circuit as long as the PV modules continue to be irradiated with light, potentially leading to a fire near the damaged PV module. The aforementioned dangers and necessary protective measures compound in complexity and risk as the PV module array grows in number and size.

Therefore, there is a need for a method and apparatus for a low cost, intelligent system for protecting and monitoring PV module operation.

SUMMARY OF THE INVENTION

Embodiments of the present invention generally relate to a method and apparatus providing a smart junction box in a PV power system substantially as shown in and/or described in connection with at least one of the figures, as set forth more completely in the claims.

Various advantages, aspects and novel features of the present disclosure, as well as details of an illustrated embodiment thereof, will be more fully understood from the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. 1 is a block diagram of a system for converting solar generated DC power to AC power in accordance with one or more embodiments of the present invention;

FIG. 2 is a detailed schematic of a smart junction box in accordance with one or more embodiments of the present invention;

FIG. 3 is a flow diagram of managing a bypass condition in accordance with one or more embodiments of the present invention;

FIG. 4 is an exemplary schematic for effectively measuring an I/V characteristic after the smart junction box is disconnected from the PV power system in accordance with one or more embodiments of the present invention;

FIG. 5 is an exemplary graph of inverter noise signatures in accordance with one or more embodiments of the present invention; and

FIGS. 6A and 6B are exemplary graphs of capacitor charging in accordance with one or more embodiments of the present invention.

DETAILED DESCRIPTION

Embodiments disclosed herein describe a method, apparatus, and system for monitoring and managing a bypass condition using a smart junction box for a photovoltaic (PV) array or module using minimal switching mechanisms. Further embodiments may include other distributed generators (e.g., wind turbines and the like) or batteries in place of the PV array.

FIG. 1 is a block diagram of a system **100** for inverting solar generated DC power to AC power in accordance with one or more embodiments of the present invention. This diagram only portrays one variation of the myriad of possible system configurations. The present invention can function in a variety of environments and systems.

The system **100** comprises a centralized power converter **102**, a smart junction box **115**, a plurality of PV modules **104₁, 104₂ . . . 104_n** (collectively referred to as PV modules **104**), a load center **108**, and generates power leading ultimately to an AC grid **106**. The PV modules **104** are coupled to

one another and to the smart junction box **115**. Two output terminals of the smart junction box **115** are coupled to two output terminals of the centralized power converter **102**. The system **100** utilizes a centralized converter topology wherein the power converter **102** inverts the DC power from the PV modules **104** to AC power (i.e., a centralized inverter). Alternatively, the centralized power converter **102** may be a DC/DC converter that converts the DC power generated by the PV modules **104** into DC at a different voltage. Other embodiments may comprise multiple smart junction boxes **115** or multiple converters **102** in a one-to-one correspondence or other ratio to each of the PV modules.

The power converter **102** comprises a DC/DC conversion module **120** coupled to a DC/AC inversion module **125** for inverting the DC power generated by the PV modules **104** to AC power (i.e., AC current); alternatively, a single stage converter may convert DC directly to AC. The power converter **102** is coupled to the AC grid **106**, which in turn is coupled to the load center **108**. In some embodiments, the load center **108** houses connections between incoming power lines from a commercial AC power grid distribution system ("grid") and the AC grid **106**. Additionally or alternatively, the AC grid **106** may be provided in off-grid applications by a battery-based (or other energy storage source) inverter and/or a rotating machine generator. The power converter **102** meters out AC current that is in-phase with the AC power grid voltage, and the system **100** couples the generated AC power to the power grid via the load center **108**. Additionally or alternatively, the generated AC power may be supplied directly to commercial and/or residential systems via the load center **108**, and/or stored for later use (e.g., utilizing batteries, heated water, hydro pumping, H₂O-to-hydrogen conversion, or the like).

In some alternative embodiments, the power converter **102** may not comprise a DC/DC converter (i.e., the power converter **102** comprises a single-stage DC/AC inverter) and a separate DC/DC converter may be coupled between the smart junction box **115** and power converter **102** (i.e., one DC/DC converter per smart junction box **115**/PV module **104** paired connection). In other alternative embodiments, the power converter **102** may be a DC/DC converter to convert the DC power generated by the PV modules **104** into DC at a different voltage. In such other alternative embodiments, the converted DC power from the power converters **102** may be supplied to commercial and/or residential DC systems, and/or the produced energy may be stored, for example, in storage batteries.

FIG. 2 is a detailed schematic of a smart junction box **115** in accordance with one or more embodiments of the present invention. FIG. 2 includes an exemplary string of PV modules **104** as part of a larger PV array (not shown). PV modules **104** may either represent groups of cells within single PV module, or individual PV modules within a PV array. The term "PV module" is thus intended to describe both such embodiments. For example, a 60 cell module may have 6 columns of 10 cells such that **104₁** may represent two columns. Other embodiments may include an inverter connected to an array of PV modules such that each module may have its own junction box. The embodiment in FIG. 2 has a system **200** comprising a smart junction box **115**, a substring of a plurality of PV modules **104₁**, **104₂**, and **104_n** (collectively referred to as PV modules **104**), and a converter **102**. Power generated by the PV modules **104** is passed through the smart junction box **115** to the converter **102** for ultimately coupling AC power to an AC grid. The exemplary embodiment of the system **200** comprises three PV modules (**104₁**, **104₂**, **104_n**), however fewer or more may be utilized. In one embodiment, the PV modules **104** are removably connected to the smart junction box **115** through input connectors (**220**, **222**, **224**, and **226**) that is in

turn removably connected through output connectors (**212** and **214**) carry DC current to the converter. Alternative embodiments include connectors that are permanently connected (e.g., crimp connected, soldered, and the like) or forego connectors for a single continuous cable.

The exemplary smart junction box **115** comprises: input connectors (**220**, **222**, **224**, and **226**), "smart" bypass diode switches (**230**, **235**, and **240**), bypass diodes (**238**, **242**, and **244**), switches (**245** and **250**), capacitors (**265** and **270**), a diode **260**, a LED **275**, a resistor **280**, a current injector circuit **255**, an Integrated Circuit (IC) chip **208**, and output connectors (**212** and **214**). In some embodiments, the smart bypass diode switches (**230**, **235**, and **240**) may be viewed as a first set of switches connected across input terminals adapted for connection to the output terminals of a plurality of photovoltaic (PV) modules and switches **245** and **250** may be viewed as a second set of switches. In other embodiments, smart bypass diode switches (**230**, **235**, and **240**) may be substituted for equivalent electrical switching mechanisms.

Input connectors (**220**, **222**, **224**, and **226**) conduct power from the PV modules **104**. All three smart bypass diode switches (**240**, **235**, and **230**) in this embodiment are transistors that have gates connected to and controlled by the IC chip **208** and in some embodiments may be integrated into the IC chip **208**.

Connector **224** is coupled to the IC chip **208** and connector **226** is connected to a power bus **236**. Connectors **224** and **226** are coupled for monitoring voltage across PV module **104_n**, and reverse current across smart bypass diode switch **240** and bypass diode **244** that are placed in parallel between connectors **226** and **224**. Other embodiments may include a controller or other processor with electronic memory in place of or included on the IC chip **208**.

Connector **222** is coupled for monitoring voltage and possible reverse current across PV module **104₂** and is connected to the IC chip **208**. Smart bypass diode switch **235** and bypass diode **242** are placed in parallel between connectors **224** and **222**. Connector **220** is connected for monitoring voltage and possible reverse current across PV module **104₁** and is connected to the IC chip **208** through a power bus **234**. Smart bypass diode switch **230** and bypass diode **238** are placed in parallel between connectors **222** and **220**.

Bypass diodes (**238**, **242**, and **244**) are across the source and drain of respective smart bypass diode switches (**230**, **235**, and **240**) comprising MOSFETs or more particularly in some embodiments, NMOS transistors. The bypass diodes (**238**, **242**, and **244**) in this configuration, shunt the current across the source and drain of the corresponding FET and protect the transistor from damage by reverse current but also indicate to the IC chip **208** the presence of a reverse current biased on the bypass diodes (**238**, **242**, and **244**). Thus, switches (**240**, **235**, and **230**) are referred to in this embodiment as "smart" bypass diode switches. In embodiments implemented with MOSFETs, bypass diodes (**238**, **242**, and **244**) may represent intrinsic body diode properties of the respective smart bypass diode switches (**230**, **235**, **240**). However, further embodiments may require actual diodes placed across the source and drain of the switching device.

The IC chip **208** is also connected to diode **260** and capacitor **265** that are connected together in series across the two power buses (**234** and **236**). Diode **260** forms a peak rectifier used to filter any transient voltage into the capacitor **265** that appears on the power buses (**234** and **236**). This voltage is measured by the IC chip **208** as V_{dd}. A capacitor **270** is connected between the IC chip **208** and the first power bus **236** for tracking the I/V curve operation of the PV modules **104**.

Switch **245** is located in series with a current injector circuit **255** and an output connector **212** formed on the power bus **234** of the smart junction box **115**. Switch **245** is the cut off switch used in case of an arc fault or in the case of a reverse bias on the individual PV modules. The current injector circuit **255** is controlled by the IC chip **208** to inject a current stimulus in order to measure the instantaneous power characteristics and may be comprised of a current measuring transformer. The resistor **280** is placed on the power bus **236** to measure output current of the smart junction box **115** using the IC chip **208**. Switch **250** is placed in parallel across the two power buses (**234** and **236**) and is physically located closest to the output connectors (**212** and **214**). LED **275** is an arc fault indicator light connected to the IC chip **208** and the power bus **236**.

When an arc fault occurs, an AC current going through the system **200** will be shaped with a $1/f$ slope. The arc fault in a signal can be detected through a Fast Fourier Transform (FFT). However, since there is noise regularly present in the system **200** from reactive circuit elements, fault detection may require identifying a signature signal that is indicative of the occurrence of an arc fault. The signature signal may be developed to disregard normal harmonics present within the system **200**. In some embodiments, the signature signal is predetermined or may be dynamically determined based on instantaneous operating conditions.

Analysis of the signals may use discrete interval sampling, or bins. Exemplary embodiments may have, for example 16 bins, divided across a 320 Hz spectrum such that each bin is about 20 Hz. Higher frequencies are possible to about 20 kHz. The amplitude of each bin may be analyzed such that the slope meets a predetermined threshold. Certain bins may be removed from the FFT flatness analysis of signal amplitude, since converter **102** may generate pre-determined grid harmonics on the input (DC) port. An example of FFT analysis on noise from an inverter is discussed further below with respect in FIG. 5. If there is an arc fault condition determined, the IC chip **208** then turns off switch **245** and turns on switch **250**. If the arc fault condition persists, switch **250** is turned off. The condition may be then recorded in non-volatile memory and the system **200** will not restart until the arc fault condition is resolved.

Optionally, the IC chip **208** may contain one or more of a GPS receiver **262**, RFID **264**, or a communication transceiver **268**. The GPS receiver **262** could provide the geo location of the smart junction box **115** for inventory management and theft protection. If the smart junction box **115** is detachable, the RFID **264** can be embedded in the IC for identification and improve inventory management. The communication transceiver **268** allows power line communications wherein the IC chip **208** is able to communicate with external electronics through the output connectors **212** and **214**. In alternative embodiments, the IC chip **208** may be modified to include wireless RF communication topology. In such embodiments, a communication system (not shown) is configured to communicate with the IC chip **208** and/or the smart junction box **115**. In addition to wireless communication, other embodiments may include hard wire network communications, cellular network communications, power line communications, and the like.

FIG. 3 is a flow diagram of a method **300** managing a bypass condition for the smart junction box **115**. The method **300** in some embodiments may be implemented by the IC chip **208** and the smart junction box **115**. Switches described herein are of an exemplary topology for managing a bypass condition of a PV module (e.g., a shading condition) however, other distributed generator or power source may be applied

such as a wind turbine or battery. Other embodiments may include detection of unexpected or undesirable operating conditions such as an arc fault, disconnection of a PV module, PV module failure, disconnection for maintenance, and the like.

The method **300** begins at step **301** and continues to step **303**. The output current of the smart junction box **115** is measured by a current measuring device (e.g., via current injection circuit **255** and/or measuring transformer) at step **303**. If, at step **305**, output current is determined to be negative, the IC chip **208** will open/turn off switch **245** and close/turn on switch **250** at step **325**. Turning off switch **245** disconnects the power bus **234** and turning on switch **250** short circuits the output connectors **212** and **214** to substantially bypass the smart junction box **115** and ultimately, the associated group of connected PV modules. Step **325** leads to step **330** declaring a reverse bias condition exists for the smart junction box **115** and the method **300** restarts.

However, if at step **305**, the method **300** determines the output current is not negative, the method **300** continues to step **310** to determine if smart bypass diode switches (**240**, **235**, and **230**) have reverse current across corresponding bypass diodes (**244**, **242**, and **238**) using IC chip **208**. Reverse current on the smart bypass diode switches (**240**, **235**, and **230**) indicate a possible reverse current across a particular PV module. It should be noted, that when smart bypass diode switches (**240**, **235**, and **230**) are consistently in a closed/on position, it may be necessary to periodically turn the switches off to accurately confirm the presence of a reverse current on the smart diode switches **240**, **235** and **230** during measurement periods.

If at step **310**, the method **300** determines there is no reverse current on a smart bypass diode switch (**240**, **235**, and **230**), then the method **300** restarts. However, if at step **310**, the method **300** determines there is a reverse current across a smart bypass diode switch, the diode with reverse current has its associated switch turned on at step **315**. For example, if a reverse current is detected at connector **222** and pin V2 of the IC chip **208**, a signal S2 is sent to close switch **235** to bypass the second PV module **104₂**. In other embodiments, more than one smart bypass diode switch may be closed to reflect shading of multiple PV modules and subsequent bypass of such modules.

Lastly, with the reverse current detected, the IC chip **208** indicates at step **320** a partial shading condition (or other performance impacting condition) has been detected and in some embodiments may communicate this status offsite via communication modules in the IC chip **208**. In other embodiments, the shading condition detection may also determine modifying other variables such as maximum power point tracking (MPPT) and/or monitoring within the system **100**. The method **300** then continues measuring output current at step **303**.

FIG. 4 is an exemplary schematic for effectively measuring an IN characteristic after the smart junction box is disconnected from the PV conversion system. The I/V characteristic is tracked by the IC chip **208**, and in further embodiments, may communicate the results to electronic memory and/or external circuitry. FIG. 4 depicts a configured circuit **400** of essentially how the junction box is viewed from the output perspective. Based on the output perspective of the circuit **400**, a measurement of the I/V characteristic curve of the smart junction box **115** is still possible even when taken out of service.

To begin measurement, a discharge capacitor **405** is connected to the output terminals (**212** and **214**) of the smart

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junction box **115**. Then by turning switch **245** off, it is possible to plot $I=f(v)$ by inferring

$$I = \frac{Cdv_c}{dt}.$$

An exemplary plot is discussed further below with respect to FIGS. **6A** and **6B**. V_c representing the charge of the load capacitor **405** having a capacitance value C . Voltage can then be measured on each PV module substring at the same time and each substring I/V characteristic can be derived. The value of capacitor **405** can be calibrated at the time of manufacturing for specific capacitor types, applications, and the like.

FIG. **5** is an exemplary graph **500** of inverter noise signatures in accordance with one or more embodiments of the present invention. The graph **500** is a plot of signals of current **505** versus frequency **510**. The signals include a first exemplary noise curve **515** and a second exemplary noise curve **520**. The respective curves representing noise signatures from two different inverters. A FFT was performed with a Hanning window on 2^{18} DC current data samples captured at 10 MHz to produce curves (**515**, **520**) that were smoothed with an 800 Hz sliding window. Using the captured noise signatures, arc fault detection accuracy is increased as the data can be compared to real-time operating conditions leading to less false-positive (i.e., erroneous) fault conditions.

In some embodiments, from the exemplary graph **500**, the flatness of the curve(s) is then compared with the $1/f$ curve corresponding to pink noise, which indicates whether an arc fault condition will be declared by the IC chip **208**. Pink noise or “flicker noise” is a signal or process with a frequency spectrum such that the power spectral density (energy or power per Hz) is inversely proportional to the frequency. If there is an arc fault condition determined, the IC chip **208** then turns off switch **245** and turns on switch **250**. If the arc fault condition persists, switch **250** is turned off. The condition may be then recorded in non-volatile memory and the system **200** will not restart until the arc fault condition is resolved. In some embodiments, the noise is present from artifacts of power conversion, be it DC-DC or DC-AC conversion generated by power conversion equipment such as inverters.

FIGS. **6A** and **6B** are exemplary graphs with data for capacitor charging in accordance with one or more embodiments of the present invention. FIG. **6A** is a graph **600** of a charging curve **615** of a capacitor (e.g., discharge capacitor **405**) against voltage **605** versus time **610** (in seconds). In this exemplary embodiment, the capacitor is 1000 microfarads (μF), however, other sizes may be used (e.g., 10 μF) as well as different time resolutions (e.g., 10 μs).

FIG. **6B** is a graph **620** of current **625** versus time **630**. From a curve **635**, current I may be determined and subsequently correlated with the voltage V from curve **615**. I and V are correlated together to determine $I=f(V)$. In other words, for each time sample, the pair V , I data are recorded and plotted to form the curve $I(V)$. Thus it is possible to plot $I=f(v)$ by inferring

$$I = \frac{Cdv_c}{dt}.$$

The foregoing description of embodiments of the invention comprises a number of elements, devices, circuits and/or assemblies that perform various functions as described.

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These elements, devices, circuits, and/or assemblies are exemplary implementations of means for performing their respectively described functions.

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

The invention claimed is:

1. An apparatus for a smart junction box comprising:

a first set of switches connected across input terminals adapted for connection to output terminals of a plurality of photovoltaic (PV) modules;

a plurality of diodes connected across input terminals of each respective switch in the first set of switches;

at least one reverse current detection device on at least one output terminal of the smart junction box;

a second set of switches to selectively disconnect and short circuit output terminals of the smart junction box when a reverse current is detected, and wherein at least one switch of the second set of switches is located across the output terminals; and

a controller controlling the first and second set of switches.

2. The apparatus of claim 1, wherein the input terminals correspond to detachable connectors for coupling to parallel connections across the plurality of PV modules.

3. The apparatus of claim 2, wherein at least one switch of the first set of switches are each coupled in parallel across each PV module.

4. The apparatus of claim 1, wherein the controller detects a reverse current at the input terminals.

5. The apparatus of claim 4, wherein the controller closes at least one switch of the first set of switches to electrically bypass a corresponding PV module.

6. The apparatus of claim 1, wherein upon detection of a reverse current, the controller communicates a notification via a communication module.

7. The apparatus of claim 1, wherein the reverse current detection device injects a stimulus current.

8. A system for a smart junction box:

a plurality of photovoltaic (PV) modules;

a power converter;

a smart junction box, the smart junction box coupled between the plurality of PV modules and the power converter, wherein the smart junction box comprises:

a first set of switches connected across input terminals adapted for connection to output terminals of the plurality of PV modules;

a plurality of diodes connected across input terminals of each respective switch in the first set of switches;

at least one reverse current detection device on at least one output terminal of the smart junction box;

a second set of switches to selectively disconnect and short circuit output terminals of the smart junction box when a reverse current is detected, and wherein at least one switch of the second set of switches is located across the output terminals; and

a controller controlling the first and second set of switches.

9. The system of claim 8, wherein the input terminals correspond to detachable connectors for coupling to parallel connections across the plurality of PV modules.

10. The system of claim 9, wherein at least one switch of the first set of switches are each coupled in parallel across each PV module.

11. The system of claim 8, wherein the controller detects a reverse current at the input terminals.

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12. The system of claim **11**, wherein the controller closes at least one switch of the first set of switches to electrically bypass a corresponding PV module.

13. The system of claim **8**, wherein upon detection of a reverse current, the controller communicates a notification via a communication module. 5

14. The system of claim **8**, wherein the reverse current detection device injects a stimulus current.

15. A method of electrical bypass using a smart junction box comprising: 10

coupling a smart junction box across output terminals of a plurality of photovoltaic (PV) modules;

monitoring input current across input terminals adapted for connection to the output terminals of the plurality of PV modules; 15

controlling via a controller a first and second set of switches;

selectively controlling the first set of switches coupled across the input terminals, and a plurality of diodes connected across input terminals of each respective switch in the first set of switches; 20

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measuring reverse current with at least one current measurement device on at least one output terminal of the smart junction box; and

controlling a second set of switches to selectively disconnect and short circuit output terminals of the smart junction box, wherein at least one switch of the second set of switches is located across the output terminals.

16. The method of claim **15**, wherein the input terminals correspond to detachable connectors for coupling to parallel connections across the plurality of PV modules.

17. The method of claim **16**, wherein at least one switch of the first set of switches are each coupled in parallel across each PV module of the plurality of PV modules.

18. The method of claim **17**, further comprising detecting a reverse current at the input terminals.

19. The method of claim **18**, closing at least one switch of the first set of switches to electrically bypass the corresponding PV module when a reverse current is detected at the input terminals.

20. The method of claim **15**, further comprising injecting a stimulus current to detect a presence of a reverse current.

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